IV

BICENTENARY OF JAMES WATT, PIONEER OF THE STEAM ENGINE[1]

IN 1711, an English blacksmith was doubtless experiencing that mixture of fear and pleasurable anticipation which always comes to a man about to test on a commercial scale an idea over which he has worked long and hard. In this case the idea was the use of heat from fuel to drive a water pump, with steam serving as a working medium. No one had as yet really used fuel as a source of work on a commercial scale, although there was a strong demand for an addition to the world's sources of power. For centuries, these sources had been limited to flowing water (which was not often available where and when wanted), to the still more unreliable wind, and to expensive slave and animal labor. Those sources permitted a standard of living in Europe which seems decidedly simple today; but the maintenance of even those standards was in 1711 becoming a serious problem in certain fields. The difficulties were especially noticeable in mining, where deeper workings caused more and more trouble with hoisting and pumping; so this inventor had worked for a number of years on a device he hoped would supersede horses as a motive power for unwatering mines. At last certain owners of a coal mine, harassed by expenses for hay, oats,

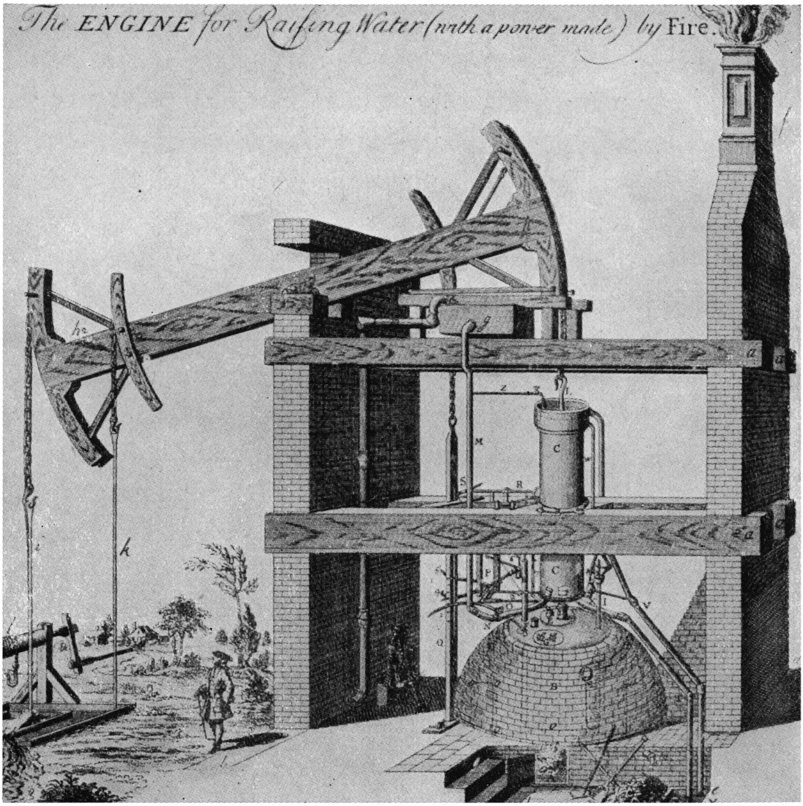
[1] Of the illustrations appearing in the course of this lecture the author is indebted to the courtesy of the Newcomen Society for No. 2 and of the University of Glasgow for No. 3, while Nos. 1, 4, 5, 6, and 7 are reproduced from *James Watt and the Steam Engine* by the kind permission of Messrs. Dickinson and Jenkins.

and worn-out horseflesh, had authorized him to supply their colliery with one of his fire-engines.

The machine to which his hopes were pinned consisted of a boiler generating steam at atmospheric pressure, a vertical cylinder closed only at the lower end and containing a single-acting piston chained to one end of a walking beam, and a reciprocating pump attached to the opposite end of the beam. We do not know exactly how this first engine operated, but apparently its cycle was something like this: the piston being held at the upper end of its stroke by the weight of the pump rods, steam was admitted to the cylinder. Then the steam valve was closed and water was sprayed on the outside of the cylinder, causing condensation of the steam and the formation of a vacuum below the piston. Atmospheric pressure acting on the upper face of the piston forced it down, thus lifting the pump rods and the water in the pump cylinder. Next, opening a valve at the bottom of the cylinder drained the condensed steam back to the boiler by gravity and supplied a fresh cylinder full of steam at atmospheric pressure, equalizing the pressure on both sides of the piston. The weight of the pump rods then lifted the piston, and with the closing of the valve the engine was ready for another cycle. Because the piston always leaked, a layer of water was provided on top of it to prevent the leakage of air from spoiling the vacuum in the cylinder.

This layer of water was responsible for one of the first improvements applied to this machine. An engine was discovered running much more rapidly than usual. Investigation showed a crack in the piston which allowed cold water to enter the cylinder, thus forming the vacuum more rapidly than before. Thereafter, the cooling water was sprayed into the cylinder itself instead of on its outer surface.

Since the motion of the piston was due to the pressure of



Courtesy of the Newcomen Society

Figure 2. Drawing of Newcomen engine made by Beighton in 1717

the atmosphere, this engine is often termed an atmospheric engine; and because the force per square inch could never be great, the diameter of these pistons was always large—usually between thirty and sixty-six inches.

The builder of this engine, Thomas Newcomen, soon had good reason to be pleased with his invention. He had customers for three more engines in the next three years, and before his death some eighteen years later he had seen them widely adopted all over Europe for pumping at coal and tin mines. Legend says that in 1713 a lazy boy named Humphrey Potter lost his job of turning the steam and water valves because he tied the handles of these cocks to the beam by cords, thus making the engine entirely automatic and capable of fifteen or sixteen strokes a minute instead of six or eight. More reliable information tells how in 1718 Henry Beighton, later a Fellow of the Royal Society, invented the first substantial steam engine valve gear by hanging from the walking beam a heavy rod called a plug tree which carried tappets operating the valves. This construction was used with all kinds of steam engines for over seventy-five years, or until the application of the eccentric to the valve motion about the year 1800.

A drawing made by Henry Beighton himself in 1717 gives a good idea of the Newcomen engine of that date. It is single-acting, with a mechanical valve gear and with water injection into the cylinder, and it has a piston two feet or more in diameter, sealed by water from an overhead tank. This engine was being promoted on the market by an organization known as "Proprietors of the Invention for Raising Water by Fire"; and in the years 1720 and 1721—the years of the South Sea Bubble collapse—two verses of doggerel give a hint of the stock-selling activities of the Proprietors. One verse, from "The Broken Stock Jobbers" says:

> Why must my stupid fancy e'er admire
> The way of raising Water up by Fire?
> The cursed Engine pumped my Pockets dry
> And left no Fire to warm my fingers by.

The other verse, from "England's Folly," urges:

> Come all ye Culls, my Water Engine buy,
> To Pump your flooded mines and Coal-pits dry.
> Some projects are all Wind, but ours is Water,
> And tho at present low may rise here a'ter.

Since all of these developments occurred well before the birth of James Watt on January 19, 1736, just a few weeks over two hundred years ago, it is obviously wrong to state (as is sometimes done) that Mr. Watt invented the steam engine. In fact, at least three men had contributed to the idea before Newcomen built the first commercially successful engine with piston and cylinder.

In 1663, the Marquis of Worcester described hazily a steam pump which he claimed worked very well. Then in 1690, the field was entered by Dionysius Papin, a religious refugee who found employment in London as a demonstrator before the Royal Society. In his attempts to design a steam pump, he used a cylinder containing a piston floating on top of the water to be displaced. Steam at a small pressure above atmospheric was his source of power. None of his engines received any commercial application.

But in 1698, an English army engineer, Thomas Savery, secured a patent on a partially successful steam pump. It was composed of two chambers in which vacuum and steam pressure were used alternately to suck in and to discharge water, much as is done in the modern pulsometer. This pump contained no pistons. The steam pressure acted directly on the surface of the water, and the vacuum was secured by pouring water on the outside of the vessels. Both these conditions made the steam consumption very high. Moreover, the height to which it could discharge water depended upon the pressure of the steam it could command; and since this pressure was seriously limited by the weak boilers available, Savery's pump could not be used in deep mines. Newcomen's engines did not require high pressure steam; in fact, their boilers are said to have operated sometimes with manholes open to the air. In general, Savery's pumps had only small commercial success; so he combined his efforts with Newcomen, who lived only fifteen miles away. Certainly he deserves some of the credit generally given Newcomen, whose special contributions include the beam which for over a century was characteristic of commercial steam engines.

The economic value of the Newcomen engine is indicated by a description of conditions in a French mine in 1739. Before the erection of an engine, the labor of fifty horses and twenty men working twenty-four hours a day was necessary to keep the mine dry, but the engine and one man could do as well by working only forty-eight hours a week. It is not strange that the engine's popularity extended even to the British colonies in North America, where in 1753, when Watt was only seventeen, the first steam engine on this continent was installed in a New Jersey copper mine.

However, the atmospheric engine had three serious defects: first (and worst), the periodic cooling of the cylinder condensed so much hot entering steam that the coal consumption was extremely high, allowing the engine to be used only in places where fuel was cheap; second, its power output was small—usually less than 100 horsepower—because the force on its piston was small, its piston was single acting, and its cycle was performed slowly; and third, a good method of driving rotary machinery, such as shafting, was not known. This last condition practically excluded the engine from driving manufacturing plants, textile mills, flour mills, and the like. The fault was attacked by pumping water into an elevated tank, whence it flowed into an over-shot water wheel which supplied the rotary motion. Of course, such an arrangement was inefficient; it probably wasted half the engine's output in pump and water-wheel losses; but the engine with connecting rod, crank, and rotating shaft was not developed until 1780, when the Newcomen engine was about seventy-five years old and almost obsolete. All its life, the atmospheric engine was limited to pumping service; and because of its high fuel consumption and its jerky unequal strokes, it did not monopolize even that field. Water power and horses continued to be the real prime movers. Newcomen engines helped the miners and were pointing the way to better things, but they could not possibly meet even the eighteenth century's demand for mechanical energy.

Such was the power situation in 1763, fifty-two years after Newcomen's first commercial installation of a steam engine, and ten years after the erection of the first steam engine in America. In that year, James Watt, a young instrument maker employed by the University of Glasgow, received the task of repairing the model of a Newcomen engine owned by the University. From the speculations induced by this repair work followed the interest of James Watt in steam and steam engines and to a great extent the creature comforts we enjoy today.

Possibly some of this audience would trace Watt's interest in steam back to an earlier date—back to a time when as a child he is supposed to have watched the tea-kettle lid bob up and down, inspiring him with hopes of harnessing the giant within to the service of mankind. This legend, like several others relating to Watt, is based on quite shaky ground. It seems to have originated from some very different recollections dictated by a cousin fifty-odd years after the sup-

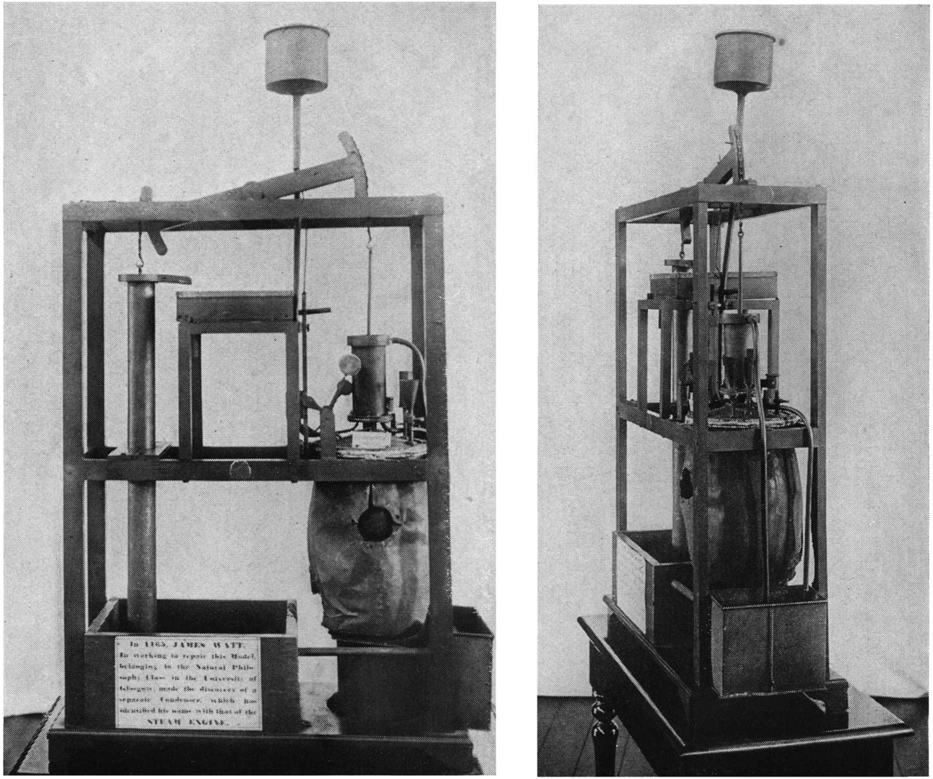


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Figure 3. Model of Newcomen engine at the University of Glasgow

posed occurrence and long after Watt had become famous enough to encourage reminiscences of his boyhood. Possibly it is even an adaptation of a story relating to the Marquis of Worcester, who while taking an enforced vacation in the Tower of London is said to have drawn similar inspiration from the pot in which his dinner was cooking. The same story is told of Newcomen too; in fact, for many years a mantel was preserved in England beneath which Newcomen's inspiration was said to have bubbled.

A second Watt legend resting on insecure foundation is that the University of Glasgow prevented the exclusion of Watt from that city by the trade guilds, who argued that he had not served a legal apprenticeship and was not the son of a Glasgow burgess. The records of the Glasgow Incorporation of Hammermen are completely silent on this point, and as a matter of fact Watt opened a small repair shop and retail store in Glasgow two years after entering the service of the University. But although these two legends about the tea-kettle and the persecution of the guilds have little basis, there is no doubt about the inspiration furnished Watt by the little engine model, now one of the treasures of the University. In return for his work on it, he received £5 11s. and an impulse which led both to his own fame and to a tremendous increase in the comfort of mankind.

At the time when Watt received this repair job, his circumstances were these: he was twenty-seven years old; he had been instrument maker to the University for six years and had made a number of valuable friends in its science faculty; he was operating a repair shop on the campus, was helping a pottery establishment with its mechanical problems, and was a partner in a retail store in the city which sold and repaired optical and navigating instruments, buckles, buttons, and ornaments. Mending flutes, guitars, and bagpipes was also a part of the activities of this business, which had a total capital of £200 and from which Watt drew an annual salary of £35. But in spite of all these activities, his total income was quite small. Soon he had the added expense of a wife and children; so the cost of his experiments with steam had to be met with borrowed money. Even time for experiment was hard to wedge into years spent in meeting family expenses and in conserving a rather delicate physique. These limitations on funds, leisure, and health, account for what seems quite slow progress in engine design during the eleven-year period between 1763 and 1774.

The question which the engine model first brought into his head was: Why does this small cylinder drain the boiler of steam in a very few strokes? The condensation of incoming steam due to alternate cooling and heating of the cylinder was the rather obvious cause; but how to avoid this condition puzzled him as much as it had Newcomen and his associates. For months the problem was an obsession to him. In April, 1765, he wrote a friend, "I can think of nothing else but this machine." But the very next month, while on a Sunday afternoon walk in the country, the answer suddenly occurred to him: he must condense the steam in a separate vessel which would be kept cold. A steam pipe and valve would connect it to the cylinder, which would be kept hot.

This idea of a separate condenser is clearly Watt's own and is of the greatest importance. Only by the use of the separate condenser could a reasonable fuel consumption be reached; and without that characteristic, steam machinery would never have given us the faithful service which means so much to our modern comfort.

To develop his idea commercially brought Watt face to face with serious difficulties, both financial and mechanical.

Already he had borrowed money for apparatus from his friend Dr. Black, professor of chemistry at Glasgow University and the discoverer of the latent heat of vapors and liquids; and his attempts at producing a geometrically true engine cylinder were to be failures for a dozen years. But at this juncture help appeared in the person of Dr. Roebuck, a physician friend of Dr. Black. This gentleman had three qualities especially useful to Watt: he was rich, he had a controlling interest in a neighboring foundry and machine shop, and he had a serious need for a machine to replace an inadequate Newcomen pumping engine. His wealth had come from two interesting sources. By amateur experiments in chemistry, he had developed a very profitable lead-chamber process for making sulphuric acid at a quarter of the former cost. From this success he turned to the mining and manufacture of iron, with special attention to artillery and large castings. His plant, known as the Carron Iron Works, gave its name to a very popular short naval cannon known as a carronade. Those of us who visited "Old Ironsides" while she was in port saw a number of them in her armament, though very possibly they did not come from the Carron Iron Works. In mining coal for his furnaces, Dr. Roebuck met the old trouble of flooded pits and found the atmospheric engine wanting. His and Watt's mutual interest was most natural. He urged Watt to push forward his experiments, which concerned the physical properties of steam and the various types of condensers. These tests were made with apparatus still in existence.

But the personal problems interfered seriously. A year after his conception of the separate condenser idea, Watt closed his shop and opened an office in Glasgow as a land surveyor and consulting engineer. For seven years, he divided his time between surveying canals and working on steam machinery with Dr. Roebuck, who soon agreed to a partnership in which he secured a two-thirds interest by assuming Watt's debts of over £1,000 and the expense of a patent covering the use of steam for power generation. In the summer of 1768, Watt applied personally for this patent and on his way home from London stopped at the factory of one of England's most prominent manufacturers, Matthew Boulton, a maker of buttons, knee and shoe buckles, steel watch chains, sword hilts, and plated ware. This experienced, optimistic, generous business man was to have an influence on the early development of the steam engine second only to Watt, who always called on Boulton for help whenever he faced business troubles. Boulton's factory employed close to a thousand men and probably was the largest in the world. But it was suffering from a very prevalent complaint: lack of water power to turn its machinery in the summer. Watt's new plans and his personality induced Boulton to negotiate for the purchase of Dr. Roebuck's interest. But the doctor was so optimistic that he not only held his share but financed the construction of a large engine on his property, with many of the parts supplied by the Carron Iron Works.

A drawing made by Watt himself late in 1768 indicates his ideas at that time. This design shows a single-acting engine with a beam; the upper side of the piston is always exposed to the boiler pressure; the lower end is connected alternately to the boiler or to the condenser by a hand-operated oscillating slide valve. The condenser is just a water-jacketed pipe, and the condensate pump is a simple affair worked from the beam. The engine for Dr. Roebuck was probably much like this drawing. We know it had a cylinder of tin eighteen inches in diameter and a quarter of an inch thick and that in one place the bore was three-eighths of an inch out of round.

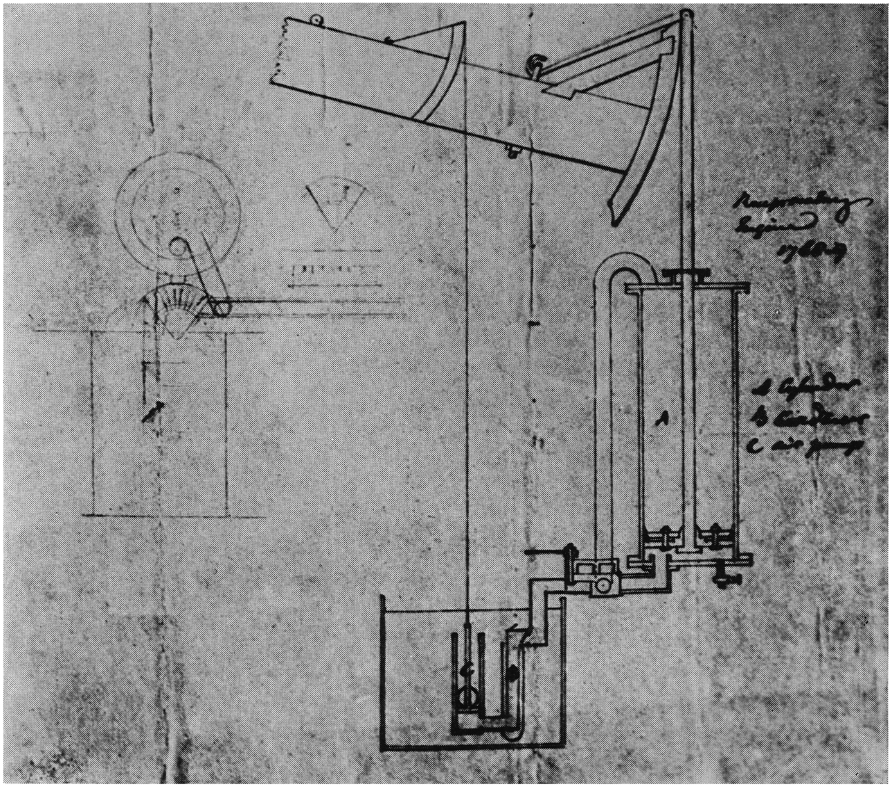

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Figure 4. Drawing made by Watt in 1769

Considering this last fact, it does not seem strange when a letter from Watt mentions as a fine job a piston fitting its cylinder within one-sixteenth of an inch all around.

With this large equipment tests were made both on the engine and on various condensers; but in the spring of 1770 work stopped for over three years. At first, Watt's canal duties interfered. He found this work reasonably profitable and interesting, and he had enough leisure to make at least two new inventions. He developed and used in his work the system of stadia measurement of distances taught to every land surveyor today, and apparently he was the first man to do so. He also described in correspondence his construction of an instrument for measuring extremely small fractions of an inch, and if the micrometer found among his tools after his death is the one of which he wrote, he probably deserves credit for inventing that extremely useful device. Had financial conditions in Great Britain been favorable, his temporary abandonment of the steam engine might have been permanent, and he might easily have developed into a distinguished civil engineer rather than into a recognized mechanical genius. But in his country the years 1772 and 1773 were those of a severe depression caused by bad harvests, commercial speculations, and very general bank failures. Canal building stopped, but so did Dr. Roebuck's contributions for engine development. In writing to a friend about future employment, Watt gives this interesting picture of himself: "I am also indolent and fearful, terrified to make bargains & I hate to settle accounts. . . . Remember in recommending me to business that what I can promise to perform is: to make an accurate survey & a faithful report of anything in the engineer way . . . to assist in the bargaining for the price of work; to direct how it ought to be executed. . . . But I can on no account have anything to do with workmen, cash, or work-men's accounts, nor would I chuse to be bound up to one object that I could not occasionally serve such friends as might employ me for smaller matters. I am not a man of regularity in Business & have bad health. Take care not to give any body a better opinion of me than I deserve, it will hurt me in the end."

He was greatly distressed over the misfortunes of Dr. Roebuck, who was definitely insolvent in 1773; but out of the wreck of his fortune came advantages to Watt and through him to the world. Matthew Boulton, who was a creditor, accepted the Doctor's interest in the steam engine as payment of his claims, and Watt was allowed to keep the large engine, which the other creditors considered absolutely worthless. An informal unwritten partnership between Boulton and Watt was promptly arranged; Watt closed his engineering office; and nine years after the conception of the separate condenser idea, both Watt and the experimental engine moved to Birmingham for a period of intensive development, under an arrangement which allowed Watt for the first time to give his whole attention to the steam engine.

These earlier delays had one effect which threatened to be serious. Six years of his patent protection were gone, and the remaining eight promised to be too few for securing enough income to meet development expenses. This fact and the inadequacy of tin as a cylinder material were two conditions receiving much attention in the autumn of 1774. In consequence, early in 1775 a cast iron cylinder was ordered, and Watt went to London to lobby for an Act of Parliament extending his patent twenty-five years. Both were secured by summer, and a new pumping engine was built in Boulton's factory. It had a cylinder diameter of eighteen inches and a stroke of five feet, used a surface condenser, and made about fifteen strokes a minute. As in the drawing of 1768,

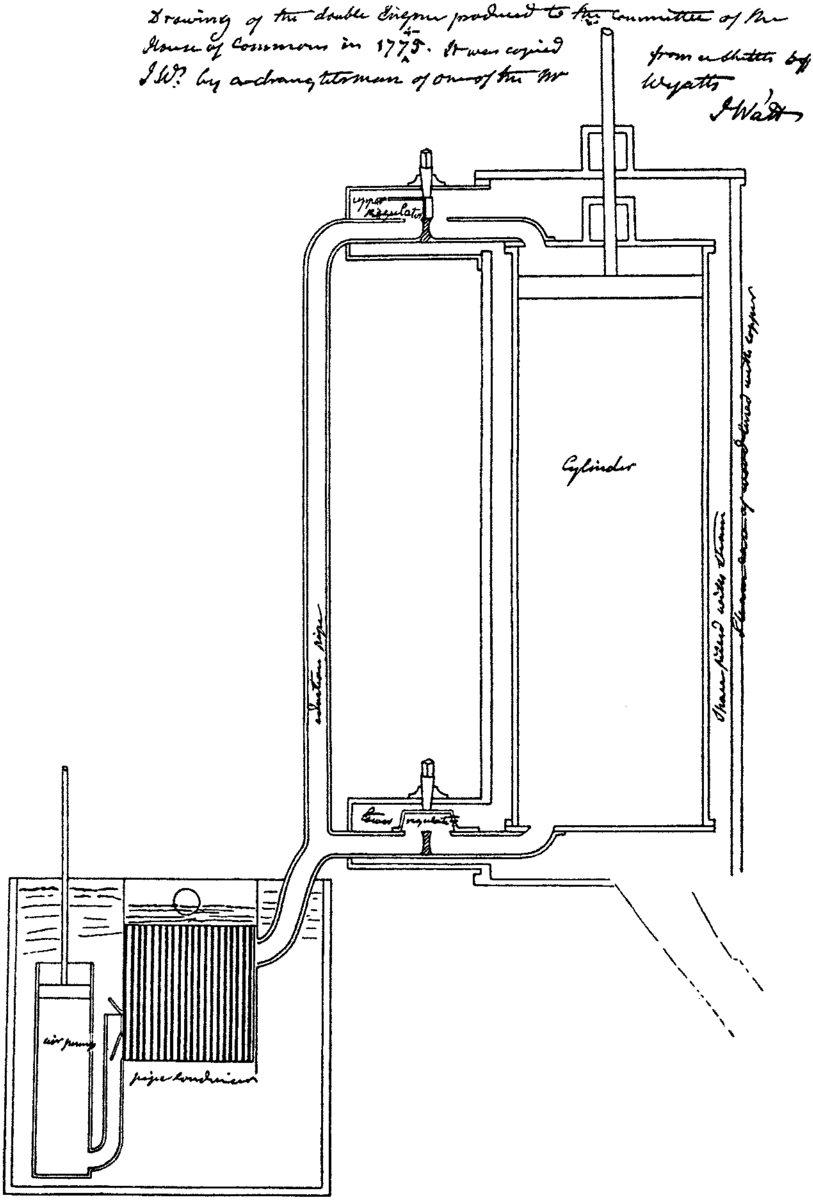

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Figure 5. Drawing made by Watt in 1775

boiler pressure always occupied the upper face of the piston. For half a dozen years, all sorts of new ideas were tried out on this engine.

By midsummer, Boulton and Watt were working feverishly on an engine for their first customer. A famous ironmaker, John Wilkinson, needed an engine to blow air into his blast furnaces, and he placed order number one. Wilkinson was a remarkable man in several ways. His first invention, a smoothing iron much used for pressing the ruffles so popular in the dress of that day, was followed by many others, including the first iron bridge, the first iron barge, and the first machine for boring cylinders with real accuracy. His interest in iron was carried to eccentric lengths. Every letter he wrote was required to contain the word iron; he built an iron chapel containing an iron pulpit; his coffin and his funeral monument were iron. His boring machine was of the utmost importance to Watt, many of whose early delays had been due to poor cylinders. The best boring machine prior to 1774 carried its cutters on a disc too flimsily supported to form a true cylinder; but by mounting the cutters on a radial arm carried by a heavy shaft rotating in stationary bearings, Wilkinson did work which Watt described in these enthusiastic terms: "Wilkinson can bore 72 inch cylinders within the thickness of a thin sixpence." This invention appeared at exactly the right time for Watt, for it is very doubtful if his or any other man's engines would have been a commercial success without the aid of Wilkinson's boring bar.

Both this engine and a coal-mine pumping engine with fifty-inch cylinder and seven-foot stroke went to work in March, 1776. Their superior fuel consumptions attracted a large number of orders and inquiries. In fact, during the summer of 1776, while Boulton's friend, Benjamin Franklin, was helping word the American Declaration of Independence, Boulton and Watt were making a very good start at the business of liberating millions of men and horses from the drudgery of power generation. Boulton the manufacturer saw clearly that their engines must eventually develop into machines adapted to rotating the shafts of mills and factories; but the most active demand was for reciprocating pumping engines, which were also the easiest type to construct. In consequence, engines with rotating shafts were not attempted for five or six years.

The pumping field alone was sufficient employment to keep Watt extremely busy for several years at designing, drafting, correspondence, and field supervision of engine erection. His method of engine construction was radically different from modern practice. Today, a machine of any sort is usually built in a manufacturing plant and shipped complete to the purchaser; but in 1776 and for twenty years after, Boulton and Watt furnished only drawings and instructions, a few of the more delicate parts made in their factory, the right to operate under Watt's patent, and the services of field erectors who were paid by the customers. Much of the engine was actually built at the plant site. This included the engine beam, the boiler, and all the forged iron work. Other parts usually came from several different foundries or machine shops. Poor transportation facilities were largely responsible for this practice. Trouble was even experienced occasionally with French privateers in the English channel or with ships whose hatches were too small to admit large castings. Working under this system, the cost to the customer of the third engine sold by Boulton and Watt was under £800. In addition to this initial expense, throughout the life of Watt's patent the engine's owner had to pay its makers a royalty of one-third of the fuel savings below the consumption of a Newcomen engine.

The demand for engines and the difficulty of securing

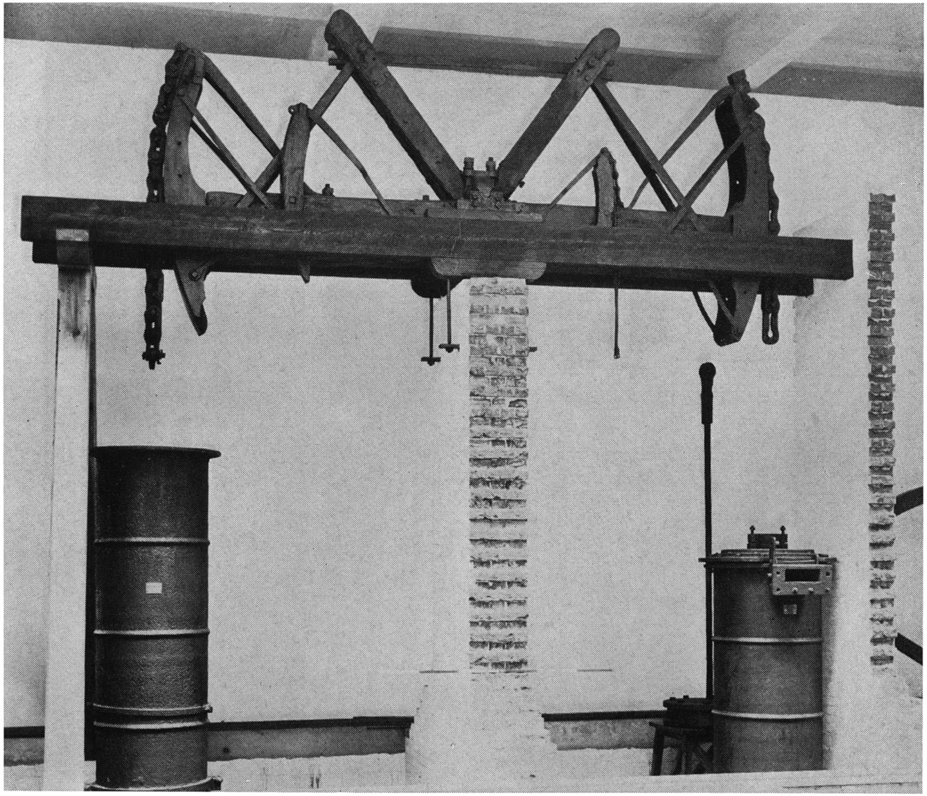

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Figure 6. Photograph of 'Old Bess' engine

properly skilled erectors kept Watt in the field many months, especially among the Cornwall tin mines. Ten engines were being constructed in 1777, and the demand for his services caused him to write home, "I fancy I must be cut up in pieces and a portion sent to each tribe in Israel." The superior fuel consumption of the Watt engine is shown by a test made on a twenty-inch engine built in 1777 to pump water in the locks of the Birmingham Canal. This small unit cost its owners £350 erected. It is probably still in working condition, for it was run under steam as late as 1919. When tested in 1778, it used 64 lbs. of coal per hour. But the best Newcomen engine would have used 194 lbs. per hour, or three times as much. If this fuel consumption decrease is typical, it is not strange that in six years Boulton and Watt had erected forty pumping engines and that only one Newcomen engine was left working in Cornwall. By 1779, engines were being exported to the Continent, where they became increasingly popular.

While these customers were being satisfied, many of Watt's other ideas remained untested. One of these was the possibility of the expansive use of steam, a plan which he had discussed back in 1769. To try it out and also to supply more power to Boulton's growing factory, a second engine was installed there in 1777. Its job was to pump water over a water-wheel which drove line shafting. Some of the parts of this engine are still in existence. Its cylinder was thirty-three inches in diameter, its stroke was seven feet, its speed was about twenty strokes a minute, a combination giving something like thirty horsepower. It worked for seventy-odd years in this factory, where it gained the name of "Old Bess." But it did not prove the value of steam expansion, largely because Watt's life-long fear of boiler explosions kept the steam pressure low, partly because the variable pressure in the steam cylinder was not well adapted to the load of a pump with no flywheel. This lack of a crank and flywheel gave even Watt's beam pumping engine a tendency to fierce and erratic action.

The tremendous press of work which almost crushed Watt between 1777 and 1780 was somewhat eased by one of his inventions which, though now quite obsolete, was indispensable to business for over a century. This was the copying book and press, which took the place occupied today by the typewritten carbon copy. In its use, letters or drawings were placed between moistened tissue paper sheets and the whole mass was squeezed firmly together by a hand-operated press. Enough ink adhered to the tissue paper so that by looking at the back of the transparent paper, a readable copy appeared. Since Watt used this system for making copies of his drawings, he is credited with having developed the first system of reproducing drawings. He patented the process and with Boulton's help manufactured the equipment as a separate enterprise under the firm name of James Watt and Co.

In June, 1779, the engine business was so good that the usually harassed and melancholy Watt wrote to Boulton the only really enthusiastic letter we have from him. The names it mentions are those of a customer and some of his mechanics. The letter says:

Dear Sir,

Hallelujah! Hallelujee!

We have concluded with Hawksbury—£217 pr. annum—from Lady Day last £275 5s. for time past £117 on account. We make them a present of 100 guineas.

Peace and good fellowship on earth—
Perrin and Evans to be dismissed—
3 more engines wanted in Cornwall—
Dudley repentant and amendant—

Yours rejoicing,
James Watt.

At the bottom of the page he adds this shamefaced post-script, "Please burn this nonsense," but Boulton evidently thought it a sufficiently remarkable letter to preserve.

After five years of operation, the engine business began to pay small profits, though the firm was deeply in debt and a new market was becoming essential. Watt wrote to a friend, "Our general expenses have hitherto been very great so that the business never paid its way before 1780, when I guess it got about £2,000 which was all swallowed up in original sin as more must be." Regarding a new market, Boulton wrote to Watt, "We must look out for orders, as all our orders are seemingly at an end, having none now on the tapis. There is no other Cornwall to be found, and the most likely line for increasing the consumption of our engines is in the application of them to mills which is certainly an extensive field." "The people of London, Manchester, and Birmingham are *steam mill mad.* I don't mean to hurry you, but I think that in the course of a month or two we should determine to take out a patent for certain methods of producing rotative motion from . . . the fire engine."

But when Watt finally came to the point of designing rotating shaft engines, unexpected patent difficulties ensued. In August, 1780, a mill owner had secured a patent sufficiently broad to cover the crank-and-connecting-rod method of turning reciprocating motion into rotary motion. Certain records show that one of Watt's workmen, perhaps under the influence of drink, gave his employer's plans away during an ale-house conversation with this competitor's employee. That story is, however, another of the several Watt legends whose details are quite uncertain. A definitely established fact is that Watt angrily refused either to buy the rights to the use of the crank or to risk legal action by using this construction during the life of the patent. Instead, in the fall of 1781, just a few days after the surrender of Cornwallis at Yorktown, Watt himself patented five different methods of turning reciprocating motion into rotary motion. One of these was a swash-plate mechanism of a type recently unearthed and applied to an oil engine. Another was the interesting sun-and-planet gear which was used by Watt for a dozen years as his standard substitute for the crank.

He described this device in a letter to Boulton in these words: "I have tried a model of one of my old plans of rotative engines. . . . It has the singular property of going twice round for each stroke of the engine and may be made to go oftener around if required without additional machinery." Doubtless a little more description than this is necessary to show the characteristics of the sun-and-planet gear. If one gear (the planet) is pinned rigidly to the connecting rod and is guided by a radial link so it travels around the outside of the crankshaft gear (or sun), the sun and its shaft will be rotated. If the two gears have equal numbers of teeth, the shaft makes two revolutions for one cycle of the planet. If the planet is larger than the sun, the sun will make more than two revolutions for one cycle of the planet, and vice versa.

Practically all of 1782 was spent on rotative engine design and experiment, and in March, 1783, the first engine of this type sold a customer was ready for trial. Once more, the purchaser was John Wilkinson. He wanted this engine to run a trip hammer in his forge shop.

That same year, Watt had another important iron in the fire—the double-acting engine. Until 1783 only half of the steam engine's strokes were power strokes; the other half simply restored the mechanism to its original position. To make each stroke a power stroke had the obvious advantage of doubling the engine's output, but the mechanical changes necessary to get this result were not easily made. The chief difficulty lay in guiding the piston in a straight line. As long as the engine was single-acting, the downward pull of the piston was readily kept vertical by means of a short chain fastened to an arc on the beam. This chain was always in tension; but when an upward thrust of the piston was proposed, a different arrangement was obviously necessary. The solution universally adopted today is to fit the piston rod into a crosshead which is forced to follow a straight line by guides. But in 1783 the formation of long smooth straight surfaces such as are needed for guides was a difficult and expensive job. Moreover, the addition of guides to a beam engine greatly increased the engine room's height.

The first double-acting engine Watt built used a rack on the piston rod engaging a gear sector on the beam. Several engines of this type were built in 1783 and 1784; but in June, 1784, Watt wrote Boulton: "I have started a new hare. I have got a glimpse of a method of causing a piston rod to move up and down perpendicularly. . . . If it answers fully to expectation, about five feet in the height of the house may be saved in eight feet strokes. . . . I think it a very probable thing to succeed, and one of the most ingenious simple pieces of mechanism I have contrived." Stated briefly, his idea was this: a vertical link was pivoted in its middle to the end of the piston rod. The upper end of the link was pinned to the beam, and therefore moved through an arc centered in the beam bearings; but the lower end was pivoted through a horizontal lever to the engine room wall and therefore swung in an arc opposite to that of the beam. By making the length of the horizontal lever half the length of the beam, the upper end of the piston rod was guided in approximately a straight line. This device worked well, but it had the disadvantage of requiring extra room for the long horizontal lever. Almost immediately Watt discovered that this length could be decreased if he pinned the piston rod above the middle of the vertical link; but in a very few months another improvement occurred to him. By hanging from the beam a parallelogram of jointed links and by attaching the long lever to it near the beam bearings, he evolved the very compact mechanism known as the parallel motion. It had the added advantage of giving almost straight line motion to the air-pump piston rod, which operated the steam valves through tappets.

These two improvements of double-acting and rotary shaft operation gave Watt an engine which could be applied to drive practically any sort of machine of his day. Orders from flour mills, breweries, and iron mills crowded the facilities of Boulton and Watt to the utmost, and the mines also began using rotating engines for hoisting purposes. In fact, new uses for the steam engine continued to appear in all these fields for over a hundred years, to stop only when the convenience of interposing the electric motor between the prime mover and the driven machinery halted the direct application of engine drive to factories. Profits for the engine builders were soon so good as to take financial worries off of Watt's mind permanently.

But the mechanical design of the engine still required much attention. The massive beam was always an expensive part of the engine, and making the cylinder double-acting required strengthening this part. For single-acting engines, it was often 30″ by 30″ by 24 feet long, of the best oak timber. In 1784 it cost perhaps £600. For double-acting engines, kingposts and stays were often added at first; but by 1800, cast iron beams began to be used, and ten years later they were always applied. The mechanism operating the two steam and two exhaust valves was also improved.

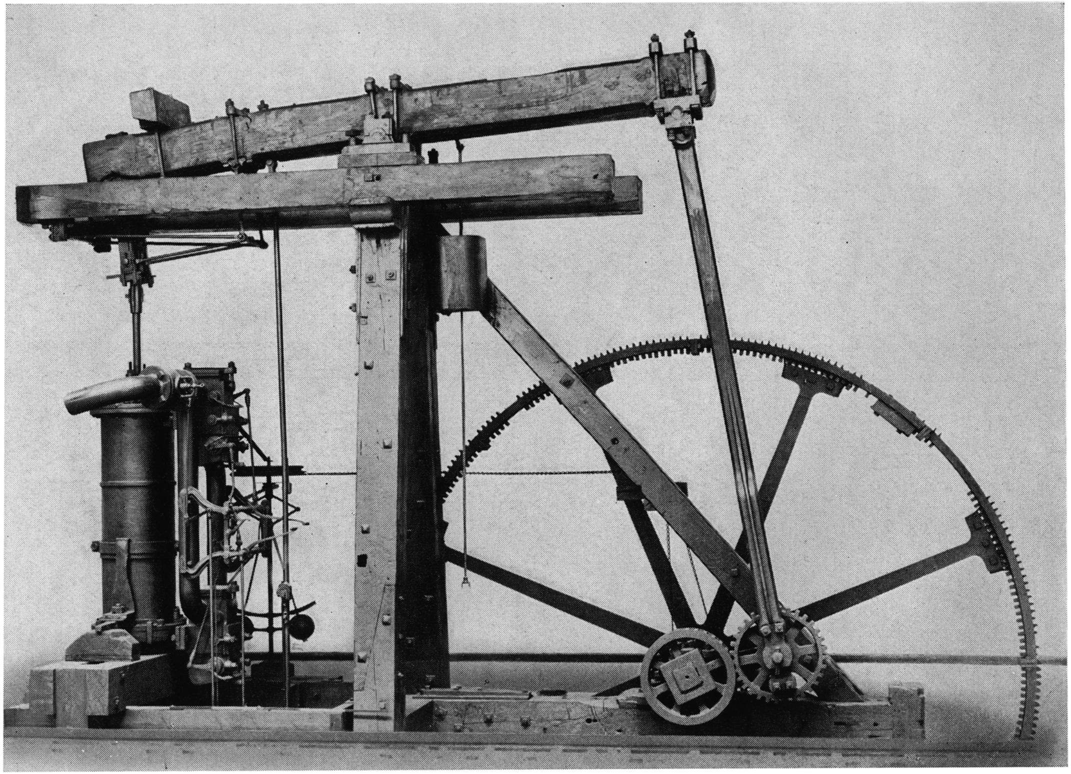

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Figure 7. Photograph of the Lap Engine, 1788

Another of Watt's activities of 1782 and 1783 helped put his name into the mouth of every user of electricity or steam power. This was his determination of the horsepower. Savery and other men had described the working capacity of Newcomen engines in terms of the number of horses displaced by the engine, a unit which though highly indefinite seemed at that time entirely natural as to name and size. But no one had attempted to define the power of a horse until in 1782 Watt adopted the figure 32,400 ft. lbs. per minute. Later he switched to the figure 33,000 ft. lbs. per minute which is universally used today. It is based on the observed ability of a brewery mill-horse to walk at two and a half miles an hour while raising 150 lbs. tied to a rope running over a pulley.

The horsepower continued to be the standard unit of power output until 1889, when the need for an electrical unit of power was apparent. In that year, the International Electrical Congress defined such a unit and gave it and its larger commercial unit the names watt and kilowatt, thus putting Watt's name frequently on the tongue of all civilized people. In that way, the Congress erected to him a monument much more durable than stone or bronze—possibly one even more enduring than the reciprocating steam engine itself.

The last of Watt's engine inventions of primary importance appeared in 1788, when he applied to an engine in Boulton's factory his rotary governor for producing constant speed at the engine's crankshaft. This engine stands today in the Science Museum at London, the first engine to be made complete with all the major contributions of Watt to the steam engine, i.e. the separate condenser, the double-acting cylinder, the parallel motion, steam expansion, the sun-and-planet gear, the flyball governor. The governor was an immediate success, and once more a shower of orders descended upon the hard-pressed factory.

Some time in the next two years, Watt is thought to have invented the steam engine indicator, a device in universal use today in determining the behavior of fluids in engine cylinders. It is essentially a pressure gauge which makes a graphic record of pressure changes on a paper chart moved in step with the engine's piston. So valuable was this instrument that Watt kept its existence secret for many years; hence we are unable to tell just how much of the invention was Watt's and how much was due to his chief draftsman John Southern, whom he hired on the peculiar condition that Southern give up his interest in music, which Watt insisted would have a bad effect on his engineering activities. Some forty years later, another Glasgow instrument maker, John McNaught, invented the oscillating drum now always used in place of Southern's reciprocating carriage.

During the hectic twelve years between 1775 and 1787, when Watt was placing before a greedy world the inventions just described, he was far from lacking in general social and scientific interests. For example, he belonged to a Birmingham club of kindred spirits known as the Lunar Society, so called because they always met for dinner and scientific discussions on the Monday nearest the full moon. Some of their number, like Josiah Wedgwood the potter and Dr. Erasmus Darwin, lived outside the city and presumably they wished the moonlight to help them get home. One distinguished member of this group was Dr. Priestly, the discoverer of oxygen and some eight other gases. Another, Dr. Darwin, the grandfather of the naturalist Charles Robert Darwin, was the author of *The Botanic Garden,* a book of verses very popular in his day. It was he who wrote this alliterative prophecy:

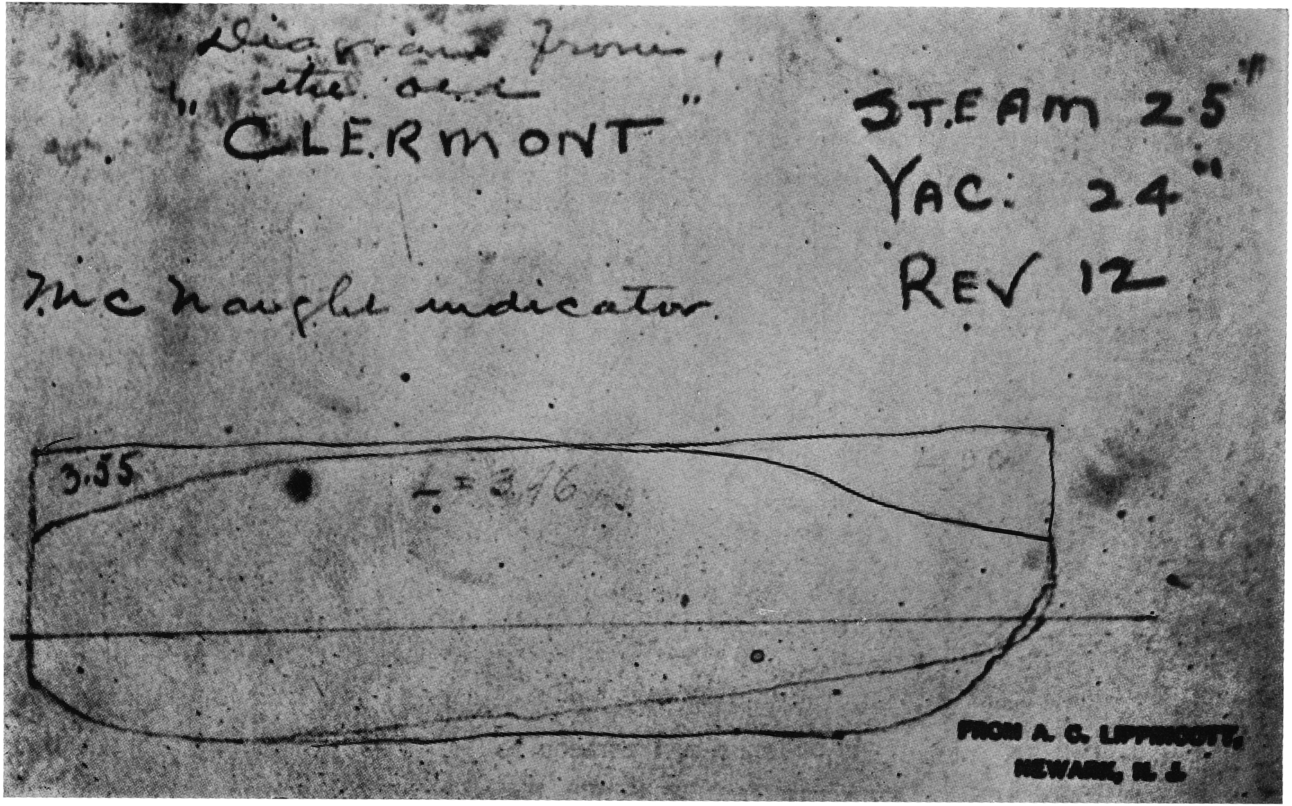

Figure 8. Indicator diagram from the Clermont

> Soon shall thy arm, unconquered steam, afar
> Drag the slow barge or drive the rapid car;
> Or on wide waving wings extended, bear
> The flying chariot through the fields of air.

To this group, Watt presented in 1783 a discussion of the constitution of water. At his friend's suggestion, he prepared his theory in a paper which Dr. Priestly was to present for him to the Royal Society; but delays in collecting experimental data allowed Cavendish to present his results first and to receive credit in many quarters for discovering that water was made of oxygen and hydrogen. There is, however, even today some difference of opinion as to whether Watt or Cavendish should have credit for discovering this fact. Watt always thought that the honor should be his.

By 1794, when Watt was fifty-eight years old, he was able to retire gradually from the engine business, placing its control in the very capable hands of a son of Boulton and a son of Watt. These two young men soon began the modern practice of making the complete engine in their factory and selling it for a fixed sum. Eight years after Watt's retirement, the firm built a horizontal double-acting engine which drove the paddle wheel of the first British steamboat, a tug-boat which was not a commercial success. In 1807, twelve years before the death of James Watt, one of their customers was Robert Fulton, whose steamboat "Clermont" was powered by a nineteen horsepower Boulton and Watt engine with a cylinder twenty-four inches in diameter by four feet stroke. Thereafter the firm became very busy in the new and profitable field of marine engine building.

Watt's later years were spent in a most interesting period in which to live—a time of rapid growth strikingly comparable to the past thirty years. In place of our World War we can put the Napoleonic conflicts; in place of the Russian, German, and Italian Revolutions we can put the French and American Revolutions; in place of our modern manufacturing and scientific men we can nominate several score pure scientists like Davy and Charles and as many pioneers of the Industrial Revolution like Eli Whitney and Arkwright.

In all these changes Watt took a quiet interest. Unlike so many inventors who lacked a Matthew Boulton to love them and pull them up to success, Watt received both financial and social recognition of his contributions to civilization long before the end of his life. Sir Walter Scott describes him in 1817 in these words: "In his eighty-fifth year, the alert, kind, benevolent old man had his attention alive to every one's question, his information at every one's command.

"His talents and fancy overflowed on every subject. One gentleman was a deep philologist,—he talked with him on the origin of the alphabet as if he had been coeval with Cadmus; another, a celebrated critic,—you would have said the old man had studied political economy and belles-lettres all his life,—of science it is unnecessary to speak, it was his own distinguished walk . . . , we discovered that the gifted man of science was . . . as shameless and obstinate a peruser of novels as if he had been a very milliner's apprentice of eighteen."

Certainly a quiet interested old age was no more than Watt deserved from the world he had served so well. The social and economic results of his inventions are so vast as almost to prevent description. How can a civilized person of today avoid the influences of steam machinery? Perhaps this might be done by moving deeply into jungles and arctic wastes, but how many of us wish to abandon the creature comforts and the mental satisfactions of today's civilization? Matthew Boulton was entirely right in telling Dr.

Johnson's friend Boswell: "I sell here, sir, what all the world desires to buy,—POWER." This power is, of course, the reason why modern nations risk serious wars for the sake of coal and oil deposits; and it was Watt's key which unlocked the tremendous supplies of energy latent in these fuels.

One way of appreciating the value of that key is to imagine the effects of its sudden loss. To take away Watt's contributions to steam engineering would practically deprive us of electricity and of liquid fuels and would make most of our machinery worthless. It would put us in a very painful way back into the material civilization of George Washington—back into the days of the tallow candle and the treadmill, for without power from fuel how could we secure large quantities of electricity for lamps or motors?—back into the days of stage coach and sailing ship, when journeys took weeks instead of equal numbers of days, and when there was good reason for inaugurating a president of the United States four months after election day; back into the days of handcrafts and cottage industries, when clothing was handwoven, handmade, and expensive, when twelve hours was a fair working day and seven years a common term of apprenticeship, when the family of a skilled workman lived in two or three rooms, on a limited diet conspicuously free from the influence of refrigeration, when printing and papermaking were done by hand and newspapers contained one or two sheets; back, doubtless, to a thinner population and a shorter length of human life.

It may be argued that outside of railroad service the reciprocating steam engine is no longer our chief source of power. It is true that tremendous amounts of the horsepower supporting our civilization come from steam turbines or internal combustion engines; but without the reciprocating steam engine we should hardly have developed these its more complex rivals. For over a century, during which time our manufacturing and electrical developments were worked out, the steam engine was the giant of prime movers and the mainspring of industry and transportation. Without its aid, many of our industries and many of our nations would still be unborn. Whatever its ultimate future may be, one cannot deny that its inventor laid one of the largest foundation stones beneath today's and tomorrow's machine-supported civilization.

J. H. POUND.